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FLOW OF GAS-PARTICLE MIXTURES.(U)  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Two-phase supersonic flows dominate the structure of exhaust plumes of rocket engines with metallized propellants. Recent study has focuses on the prediction of the characteristics of these exhaust plumes in order to evaluate plume visibility, radiation signatures and impingement effects. The objective of this study is to provide new experimental data on particle concentration, size distribution, transport effects, and particle interactions with shock waves in two phase jets. Progress in these measurements is decided in this annual scientific report.		

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## FLOW OF GAS-PARTICLE MIXTURES

AFOSR-77-3103

1. Research Objectives

There are many practical examples of engineering systems in which small, solid particles are mixed with a gas and the mixture flows through the system. The visible trailing plume from a rocket engine is formed in part by burning of small particles flowing from the rocket engine when they mix with the air in the atmosphere. These particles can also collect on the outer surfaces of spacecraft windows and reduce transmission and reception of light used for navigation and scientific data collection. When finely crushed powders of coal (pulverized coal) are burned in a power plant the coal powder must be sprayed with a nozzle into the boiler and mixed with air before it can burn. One method for producing a synthetic natural gas (entrained gasification) is to spray powdered coal into a heated gas mixture containing steam and hydrogen under carefully controlled conditions. Mixtures of small particles and gases also occur in aircraft engines, diesel engines, and woodburning fireplaces and stoves.

Understanding of these flows with gases and particles is necessary to design the systems and predict their performance. For example, how fast the particle burns depends on how far into the surrounding air it moves and how much air it is exposed to. Unfortunately, these flow systems are very complex and poorly characterized even though they occur so frequently. The particles usually move in a different direction than the gas, with a different speed and a different temperature. All of these quantities should be known to design the practical system and they are influenced by the spray nozzle shape and gas flow. Because the particles are so small (about one millionth of a meter), measurements on the system are difficult. In addition, particles of different size and shape move to different locations in the gas flow. Careful measure-



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ments under well characterized conditions are needed to understand the flow and to develop an ability to design the flow.

Previous studies of two phase round jet flow have been reviewed in considerable detail in recent reports describing our experimental results (Hayashi<sup>1</sup>, Hayashi and Branch<sup>2,3</sup>). In dilute two phase jets with few solid particles, Hetsroni and Sokolov<sup>4</sup>, and Popper, et al<sup>5</sup> showed that the solid particle velocity is higher than the gas velocity in many regions of the jet. Other authors have investigated the characteristics of turbulence in a suspension of solid particles. Goldschmidt et al<sup>6</sup> and Hedman and Smoot<sup>7</sup> showed that turbulent transport is dependent on particle size distribution. Other studies have reported that the turbulent energy level decreases with the suspension of particles into a jet<sup>4,8</sup>. Carrier<sup>9</sup> showed theoretically that behind a shock wave the velocity of the gas is smaller than the velocity of the suspended particles and that the particles are then decelerated. Korkan et al<sup>10</sup> observed no change in the particle direction through an oblique shock wave, even though the gas does change direction.

The studies considered above are for systems with few particles in the flow. There is a significant lack of detailed experimental characterization of gas particle jets in flow with high particle concentration where particles can interact or collide. Among the uncertainties are axial and radial particle velocity lag, effects of gas turbulence on the particle, particle size variation in the flowfield, effects of nonspherical particles and particle drag coefficients. These data are necessary both to develop phenomenological models of two phase jet flow and to provide comparison data for evaluation of theoretical models. A second area of almost no current understanding and experimental characterization is particle interactions with shock waves in these flows. This is particularly true of oblique shock waves. The details of flow of particles and gas in passing through a shock wave are needed to evaluate the important processes describing the interaction in order to model these effects.

## II. Status of Research

This report summarizes studies being conducted to characterize the flow of a gas particle mixture in a round jet including the characterization of particle interactions with pressure waves formed in the jet in high speed compressible flow. Recently developed systems using light to make the measurements have shown great promise in making these measurements.

Recent results of the studies have included measurement of particle location and concentration, velocity, size distribution and shock wave structure for comparison to computation results. The flows of primary interest are nozzle and jet flow with micron-sized particles. Specific measurements in the study are outlined below.

### 1. Velocity

Axial and radial velocity distribution of particles in the round jets and before and after shock waves in the flow are measured by a laser anemometer. This system provides data on particle velocity and turbulent fluctuations. By seeding the flow with a low loading of very small particles that do move like the gas, velocity and turbulence characteristics of the gas may be obtained as well.

### 2. Particle Concentration

Optical techniques developed previously (Hayashi and Branch<sup>2</sup>) are used for measurement of particle concentration and for flow visualization. Particle concentration is measured by recording scattered light from a thin sheet of light focused through the centerline of the jet and by interpretation of the photographic record with an integrating densitometer (Figure 1). Conventional laser schlieren systems will be used for visualization of the shock wave location and structure in the jets (Figure 2).

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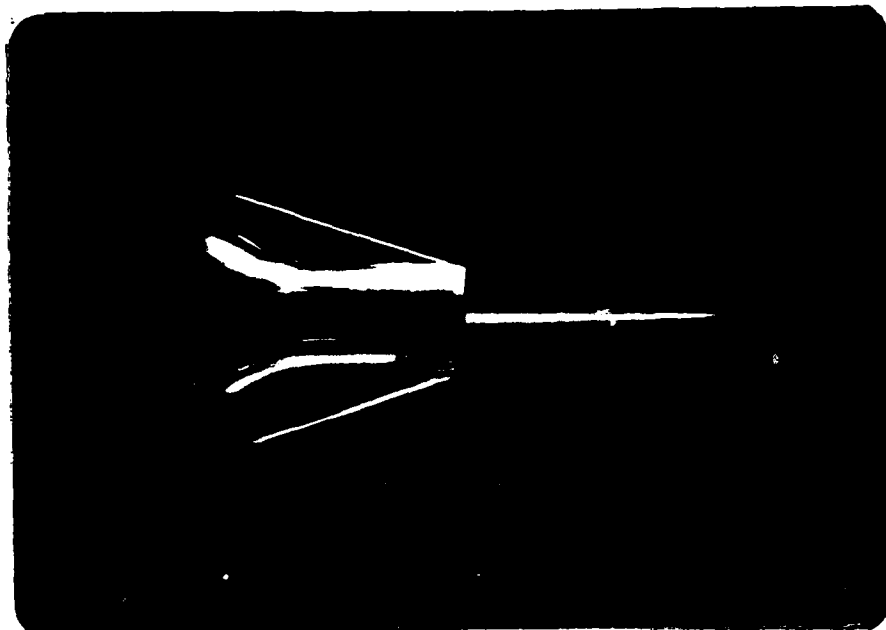


Figure 1. Flow visualization of particles concentrated along the centerline of a round jet moving from left to right out of a flow nozzle. The particles are concentrated along the axis because of their greater momentum. The gas surrounding the particles is accelerated in the nozzle and generally travels faster than the particles. Mechanical Engineering Combustion Laboratory Photograph.



Figure 2. A laser schlieren photograph of shock waves (pressure waves similar to a small sonic boom) in a very high speed round jet. The pressure waves include oblique (angled) shock waves and curved shock waves due to the particles which can be seen in the center of the flow. Without particles the oblique shock waves are at a different angle and the curved shock waves are straight. The shock waves are visible because light traveling through the shock wave changes direction and the photograph is not exposed and appears dark where the shock wave is located. Mechanical Engineering Combustion Laboratory Photograph.

### 3. Particle Size Distribution

Particle sampling probes are used to extract particles from the flow. The samples are then analyzed by a scanning electron microscope and a Coulter counter for measurement of size distribution.

### 4. Flow Computation

Finite difference computer codes for nozzle and jet flow under development at Aeronautical Research Associates of Princeton seem best suited for comparison to our experimental results. The Standardized Performance Program (SPP) is used for nozzle flow correlations and the Standardized Plume Flow (SPF) code is under development for jet calculations including particle/shock interactions. Both are being supplied for use in the project.

This project provides an exciting opportunity to use the most recent methods for experimental measurements, including some we have developed, to study a system of wide ranging practical importance and to contribute substantially to the understanding of these systems.

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### III. Publications

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2. K. Hayashi, "Measurement and Calculation of Properties of Gas-Solid Two-Phase Jets," PhD Thesis, Mechanical Engineering Department, University of Colorado, Boulder, Colorado, December 4, 1980.
3. K. Hayashi and M.C. Branch, "Oblique Shock Waves in Two Phase Flow," Eighth International Colloquium on Gasdynamics of Explosions and Reactive Systems, Minsk, USSR, August 23-26, 1981; also Progress in Aeronautics and Astronautics, in press.
4. K. Hayashi and M.C. Branch, "Particle Transport Effects in Gas-Solid Two-Phase Nozzle and Jet Flow," Paper No. 81-2100, AIAA 14th Fluid and Plasma Dynamics Conference, Palo Alto, CA, June 23-25, 1981.
5. K. Hayashi and M.C. Branch, "Interaction of Particles with Normal and Oblique Shock Waves," to be submitted to Israel Conference on Mechanical Engineering, Tel Aviv, July 14-16, 1982.
6. K. Hayashi and M.C. Branch, "Flow of Gas-Particle Mixtures," Progress in Energy and Combustion Science, in preparation.

IV. Personnel

1. Melvyn C. Branch, Associate Professor of Mechanical Engineering, Project Director and Principal Investigator.
2. Koichi Hayashi, Research Assistant. Awarded PhD in Mechanical Engineering December 1980. Thesis title: "Measurement and Calculation of Properties of Gas-Solid Two Phase Jets". Currently Postdoctoral Fellow, Princeton University, Princeton, New Jersey.
3. Gary Shamsioian, Research Assistant.
4. Lionel Poincenot, Research Assistant.

#### V. Interactions

Formal presentations of results obtained in this study have included a paper presented at the AIAA 14th Fluid and Plasma Dynamics Meeting in June 1981 entitled "Particle Transport Effects in Gas-Solid Two-Phase Nozzle and Jet Flow." An oral progress report and abstract entitled "Flow of Gas Particle Mixtures" was presented at the AFOSR/AFRPL Rocket Propulsion Research Meeting, March 1981 in Lancaster, California. A paper was also presented at the Eighth International Colloquium on Gas Dynamics of Explosions and Reactive Systems in 1981.

Interaction with Edwards Air Force Base, California (Dr. Dave Mann) and Aeronautical Research Associates of Princeton has been maintained to determine the availability of numerical prediction codes for two-phase nozzle and plume flow. Data obtained in the present study will be compared to predictions using these codes when they become available.